



The Combined Use of Groundwater Quality, Drawdown Index and Land Use to Establish a Multi-Purpose Groundwater Utilization Plan

Ching-Ping Liang¹ · Wen-Shuo Hsu² · Yi-Chi Chien³ · Sheng-Wei Wang⁴ · Jui-Sheng Chen²

Received: 10 March 2019 / Accepted: 13 September 2019 /

Published online: 14 October 2019

© Springer Nature B.V. 2019

Abstract

Groundwater is abundant and widely used for household consumption, irrigation, and aquaculture in the Lanyang Plain in northeastern Taiwan. However, it is subject to contamination by various anthropogenic activities and natural processes, as well as overexploitation, which has led to land subsidence in the eastern coastal area of this plain. It is becoming increasingly urgent to establish a sound plan for groundwater resource management in the Lanyang Plain to ensure the safe and sustainable use of groundwater to meet demands. The aim of this study is to develop a sound management plan for multipurpose groundwater utilization in the Lanyang Plain. This plan is developed with consideration of the quality and quantity of groundwater, as well as current land use practices. First, the groundwater quality parameters are spatially mapped followed by geographic determination of regions where groundwater quality is safe for different purposes, based on the water quality criteria for drinking, irrigation, and aquaculture. Subsequently, the drawdown index, defined as the ratio of the actual groundwater utilization rate to the transmissivity, is determined for each cell and low drawdown index regions are identified geographically. Information about regions where groundwater quality is safe for different purposes and the regions where the drawdown index is low is integrated to create a map which can be used for the production of a sound management plan for multipurpose groundwater utilization in the Lanyang Plain. Comparisons between our newly created map and current land use for farmlands and fishponds can provide a basis to review the current land use practices in these regions.

Keywords Multi-purpose groundwater utilization · Kriging · Groundwater quality · Drawdown index · Land use

✉ Jui-Sheng Chen
juischen@ncu.edu.tw

1 Introduction

Groundwater is an essential freshwater resource for human consumption around the world. It accounts for a substantial portion of the freshwater supply in Taiwan's northeastern Lanyang Plain because of its abundance and rapid replenishment. Residents in the Lanyang Plain depend upon groundwater to meet their demands for drinking, irrigation, and aquaculture making up for the shortage of surface water. However, a significant reduction in groundwater levels, as well as severe saltwater intrusion and land subsidence in the coastal areas of the Lanyang Plain, caused by overexploitation, has been reported and become serious concerns over the past 3 decades.

Moreover, a long-term groundwater quality survey conducted by the Agricultural Engineering Research Center (AERC) with financial support from the Taiwan Water Resource Agency (WRA) has reported groundwater contamination, with the occurrence of chemicals such as arsenic, nitrate, chloride, sodium, manganese and iron in some of their monitoring wells (AERC 2009; 2010; 2011; 2012). Consuming contaminated groundwater is considered hazardous to human health. Exposure to some hazardous chemicals is known to cause a variety of acute and chronic problems (e.g. Jang et al. 2016a; Liang et al. 2016a). Indirectly, hazardous chemicals can enter the food chain and poses a potential threat to human health through farmed seafood and consumption of crops grown using As-contaminated groundwater for irrigation (e.g. Liang et al. 2013).

The effective management of groundwater quantity and quality is imperative to ensure continued access to clean, accessible, and plentiful groundwater supply in the Lanyang Plain. The groundwater level, groundwater quality as well as the other hydrogeological characteristics are important factors for the effective management of groundwater resources. However, in the Lanyang Plain, there is considerable spatial variation from region to region in the data for these parameters, so mapping of the spatial variability of these factors is important. Since it is so expensive and time-consuming to manually measure groundwater levels, and to sample and analyze groundwater quality and determine hydrogeological characteristics in the field, flow and solute transport models are frequently used to predict them. However, a detailed physical description of the hydrogeology and specification of the initial and boundary conditions is necessary. Both of these are dependent upon obtaining sufficient information about a number of hydrogeological parameters as well as requiring extensive computational effort. These factors have restricted the application of such models for the assessment of the groundwater quantity and quality. Geostatistical techniques are increasingly being applied for the spatial characterization of the hydrogeochemical and hydrogeological parameters including groundwater quality, groundwater levels and hydraulic conductivity (Varouchakis et al. 2012; Chica-Olmo et al. 2014; Liang et al. 2017). Lee et al. (2008) applied a multivariate indicator kriging (MVIK) approach to spatially characterize the regions in the Lanyang Plain where groundwater quality is safe for multi-purpose utilization. However, they only considered conditions affecting groundwater quality. Jang et al. (2012) established an irrigation management plan for sustainable groundwater use in the Pingtung Plain based on irrigation quality standards and aquifer transmissivity. Jang et al. (2016b) applied MODFLOW (Harbaugh and McDonald 1996), a popular numerical model for the simulation of groundwater flow and groundwater levels. They also adopted the MVIK technique for the spatial determination of regions where the groundwater quality is safe to be used for drinking, irrigation and aquaculture. A sound strategy for the joint use of groundwater and surface water in the Pingtung Plain was established by integrating the analyzed results for groundwater levels and groundwater

quality. Liang et al. (2016b) applied the ordinary kriging method (OK) for spatial determination of the regions where groundwater quality is safe for irrigation, aquaculture and drinking in the Pingtung Plain, Taiwan. They also specified the low aquifer impact zones based on the ratio of the actual groundwater extraction rate to aquifer transmissivity.

The objective of this study is to establish a sound management plan for multi-purpose groundwater utilization in the Lanyang Plain. This novel management plan can be developed with simultaneous consideration of groundwater quality, drawdown caused by groundwater exploitation and current land use information. The results of this study can assist government administrators in their development of effective groundwater resource management plans for the Lanyang Plain.

2 Materials and Methodology

This study aims to establish a sound management plan for multi-purpose groundwater utilization in the Lanyang Plain. Information about groundwater quality, the drawdown index and current land use practice is all considered simultaneously. First, the OK approach is used to estimate the spatial distribution of hydrochemical parameters related groundwater quality and evaluate safe regions for different utilization demands based on the standards for drinking, irrigation, and aquaculture. Secondly, the OK approach is used to map the spatially distribution of transmissivity and create low drawdown index regions. The drawdown index which is defined as the ratio of the actual groundwater utilization to the transmissivity is used to measure the potential negative effect induced by the groundwater exploitation. A map is created by integrating the results showing the regions where groundwater quality is safe for different purposes and regions where the drawdown index is low. The map can be used for the development of a sound management plan for multi-purpose groundwater utilization. The developed map can be compared with current land use practice to provide a tool for improving water resource management and land use practices, for prioritizing the regions where new measures need to be adopted to avoid the consumption of unsafe groundwater or overexploitation of groundwater resources by replacing groundwater withdrawal with treated surface water or where the current land use practices are needed to be changed.

2.1 Study Area

The Lanyang Plain sits in Yilan County located in northeastern Taiwan (Fig. 1) and includes the alluvial fan of the Lanyang River. It comprises ten administrative townships which contain 97% of the population (about 451,000) of Yilan County. It covers an area of 400 km² and is roughly shaped like an equilateral triangle, surrounded by mountains on three sides, the Xueshan Mountain Range and the Central Mountain Range to the north, west and the south. The east faces the Pacific Ocean. The longest distance from south to north and from west to east the longest distance is about 30 km. The Lanyang River is the major river in the area and flows from west to east, through the middle of the plain.

The area has a subtropical climate with northeasterly monsoon winds blowing as autumn changes to winter. The northeasterly monsoon winds combined with the topography produce heavy rainfall in the winter season. Convectonal rainfall can occur in the summer season due

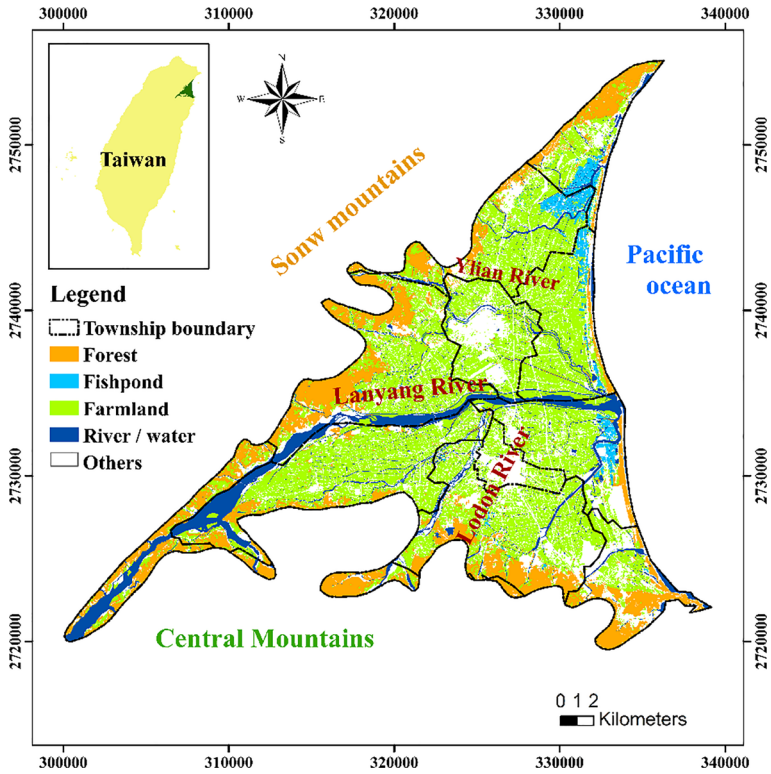


Fig. 1 Map of land use on the Lanyang Plain

to the higher temperature, with above average rainfall during typhoon season from September to December. Otherwise monthly rainfall is distributed evenly. Thus, there is ample runoff leftover to accumulate as groundwater. Analysis of the subsurface hydrogeology shows that the area underlying the plain contains one unconfined aquifer on top and several deeper confined aquifers and two aquitards (Fig. 2). The alluvial cover ranges from 100 to 400 m

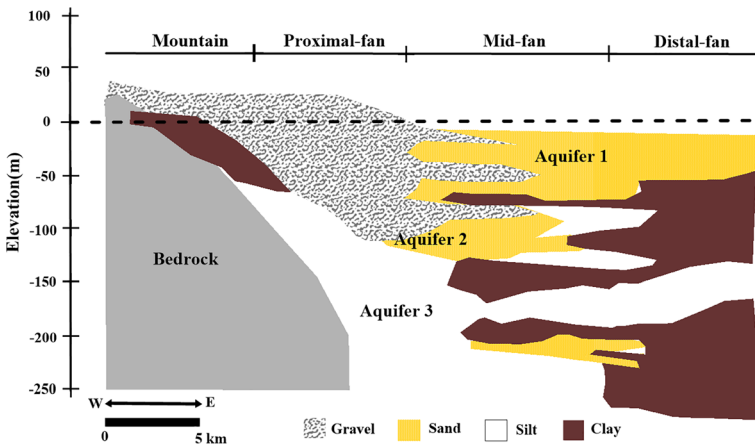


Fig. 2 Hydrogeological profile of the Lanyang Plain

in thickness. The geology underlying the plain consists of Holocene alluvial deposits which include sands, gravel clays, detrital slates, quartz sandstone, and crystallized gneiss (Lin and Kao 1997; Jean et al. 2010). The aquifers are comprised of coarse sand and gravel between the proximal area and the center of the fan. These regions are highly permeable and contribute the most to aquifer recharging. The coastal regions which are less permeable consist mainly of fine sand and clay. Groundwater flow follows the topography from the mountainous regions to the eastern coastal regions.

Lacking in man-made reservoirs, residents have taken advantage of the abundance of groundwater to supply their fresh water needs from shallow household wells (<40 m in depth) since the late 1940s (Jean et al. 2010). The Lanyang Plain is a heavily utilized agricultural area for the cultivation of crops and aquaculture, with approximately 45.7% of the area being used for agriculture and 5.1% for fishponds (Fig. 1). Supplying the water resources required for agriculture and aquaculture accounts for the major portion of groundwater utilization in the Lanyang Plain. Additionally, roughly 60% of the tap water provided by the Taiwan Water Corporation is supplied by extracting groundwater from aquifers.

2.2 Data on the Groundwater Quality and Groundwater Quality Standards

Data for groundwater quality in the Lanyang Plain is collected from the Taiwan Water Resources Agency, Taiwan Environmental Protection Administration and the Environmental Protection Bureau (EPB) of the Yilan County Government. Table 1 summarizes the descriptive statistics including the maximum, minimum, mean and standard deviation as well as 25th, 50th and 75th percentiles for each hydrochemical parameter. Table 2 summarizes the information regarding the percentage of observation wells in which the measured concentration for each individual hydrochemical parameter exceeds the water quality standards for drinking, irrigation, and aquaculture, respectively. For drinking, the measured $\text{NH}_4^+\text{-N}$ concentrations should have a maximum exceedance percentage of approximately 60%, and the measured As concentration should have an exceedance percentage of 18%. For irrigation, the measured DO concentrations should have an exceedance percentage of 63% while the exceedance percentage of the measured As concentrations is only 5.4%. For aquaculture, the measured DO concentrations should have an exceedance percentage of 79% of and the exceedance percentage of the measured $\text{NH}_4^+\text{-N}$ concentrations should be 30%.

2.3 Kriging Approach

In this study, the OK method is used to estimate the spatial patterns of each hydrochemical parameter and aquifer transmissivity. This is the most commonly used geostatistical method for mapping the spatial distribution of a random variable. The regionalized variable theory (RVT) states that a variable in an area has both random and spatially structured properties and assumes a second-order stationary process. (Journel and Huijbregts 1978). The major application of RVT is in the kriging method for spatial interpolation.

In the kriging approach, a geostatistical variogram within a statistical framework needs to be determined first. The experimental semi-variogram is used to characterize the trend of the spatial variability of a regional variable between two observation locations. In practice, the lag distance is frequently represented by a distance interval since the probability of the distance h

Table 1 Descriptive statistics of various chemical parameters (mg/L), water temperature (°C), and electrical conductivity ($\mu\text{mho}/\text{cm}25^\circ\text{C}$)

Contaminants	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn	NO ³ -N	NH ₄ ⁺ -N	Cl ⁻	SO ₄ ²⁻	DO
Average	0.014	0.001	0.005	0.005	0.427	0.0003	0.070	0.006	0.006	0.018	0.520	0.769	428	59,253	2.289
Standard deviation	0.055	0.003	0.004	0.005	3.550	0	0.292	0.003	0.003	0.027	0.725	2.457	1529	181,006	2.134
Minimum	0.000	0.001	0.001	0.001	0.016	0.0003	0.005	0.000	0.034	0.002	0.010	0.010	1.400	1.000	0.000
Maximum	0.772	0.017	0.018	0.028	97,500	0.0003	5.850	0.019	0.003	0.118	2.680	23,200	7150	1150,000	6.600
25th percentile	0.000	0.001	0.001	0.001	0.045	0.0003	0.015	0.005	0.007	0.006	0.040	0.035	3.575	9,550	0.650
50th percentile	0.001	0.001	0.006	0.006	0.045	0.0003	0.015	0.006	0.009	0.010	0.130	0.170	6.8	17,650	1.000
75th percentile	0.005	0.001	0.008	0.007	0.230	0.0003	0.030	0.007	0.007	0.017	0.893	0.380	12.65	38,300	4.250

Table 2 Water quality standards (chemicals (mg/L) and *E. coli* (CFU/100)) and the number of wells where contaminants exceed the water quality standards for drinking, irrigation, and aquaculture

Drinking water quality standard																
Contaminants	As	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Zn	NH ₄ ⁺ -N	Cl ⁻	PH	NO ₃ ⁻ -N	TOC	SO ₄ ²⁻	Total hardness
Standard ^a	0.01	0.005	0.05	1	0.3	0.05	0.1	0.01	5	0.1	250	6–8.5	10	4	250	300
Number ^b	174	1	0	0	166	173	0	3	0	566	4	15	0	7	1	2
Percentage ^c	18.1	2.5	0	0	17.3	18	0	7.5	0	59.1	10	1.6	0	17.5	2.5	10.5
Irrigation water quality standard																
Contaminants	As	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Hg	Cl ⁻	PH	EC	DO	SO ₄ ²⁻	Zn	
Standard ^a	0.05	0.01	0.1	0.2	5.0	0.2	0.2	0.1	0.002	175	6–9	750	>3	200	2	
Number ^b	52	1	0	0	8	49	0	0	0	4	12	0	12	1	0	
Percentage ^c	5.4	2.5	0	0	0.8	5.1	0	0	0	10	1.2	0	63.16	2.5	0	
Aquaculture water quality standard																
Contaminants	As	Cd	Cr	Cu	PH	Mn	Pb	Zn	DO	NO ₃ ⁻ -N	Hg					
Standard ^a	0.05	0.01	0.05	0.03	4–9	0.05	0.1	0.5	>4.5	0.3	0.002					
Number ^b	52	1	0	0	12	173	0	0	15	294	0					
Percentage ^c	5.4	2.5	0	0	1.3	18	0	0	78.95	30.7	0					

^a The water quality standards for drinking, irrigation, and aquaculture in Taiwan are available at <http://w3.epa.gov.tw/epalaw/docfile/090040.doc>, http://www.coa.gov.tw/files/web_articles_files/8655/1087.doc, and <http://law.epa.gov.tw/zh-tw/laws/3094/17667.html>

^b Numbers of wells where contaminant concentration exceeds water quality standards

^c Percentages of wells where contaminant concentration exceeds water quality standards

between pairs of observation locations being exact is low. An experimental semi-variogram $\gamma(h)$ for pairs of observation locations within a distance interval can be described by the following expression:

$$\gamma(h) = \frac{1}{2N(h)} \left\{ \sum_{i=1}^{N(h)} [Z(\chi_i + h) - Z(\chi_i)]^2 \right\} \quad (1)$$

where $Z(\chi_i)$ is the value of the regional variable of interest at observation location $\chi_i + h$; $Z(\chi_i + h)$ is the value of the regional variable of interest at location $\chi_i + h$; h is the lag distance between two observation locations; $N(h)$ is the number of pairs of observation locations separated by h with a distance interval.

The theoretical semi-variogram model provides the information regarding the spatial variability that is required for the kriging method. Based on Eq. (1), the experimental semi-variograms of the regional variable of interest created by taking into consideration all observation locations are computed and subsequently fitted to a theoretical semi-variogram model. The widely used spherical, exponential and Gaussian models are written as follows:

$$\gamma(h) = \begin{cases} c_0 + c \left[1.5 \left(\frac{h}{a} \right) - 0.5 \left(\frac{h}{a} \right)^3 \right] & h \leq a \\ c_0 + c & h > a \end{cases} \quad \text{spherical model;} \quad (2a)$$

$$\gamma(h) = c_0 + c \left[1 - \exp \left(-\frac{3h}{a} \right) \right] \quad \text{exponential model;} \quad (2b)$$

$$\gamma(h) = c_0 + c \left\{ 1 - \exp \left[-\left(\frac{3h}{a} \right)^2 \right] \right\} \quad \text{Gaussian model;} \quad (2c)$$

where c_0 indicates the nugget effect; c is the sill; and a is the range.

The OK method is considered to be an optimal spatial interpolation estimation method in which the values of the random variable $Z(x)$ at an unsampled location x_0 are determined according to the linear combination of the known values of all the sampled locations as follows:

$$Z^*(x_0) = \sum_{i=1}^M \lambda_i(x_i) Z(x_i) \quad (3)$$

where $Z^*(x_0)$ is the unknown value of the random variable to be determined at an unsampled location x_0 ; $Z(x_i)$ denotes the known values of the random variable at a sampled location (x_i) ; M is the total number of known value of random variable $Z(x)$ at the sampled location; and $\lambda_i(x_i)$ is a kriging weighting factor for the known value of random variable $Z(x)$ at a sampled location (x_i) which is used to determine $Z^*(x_0)$.

2.4 Evaluation of Drawdown Index

Physically based numerical models of groundwater flow have been widely used for quantifying changes in groundwater levels caused by man-made withdrawal and other

hydrological events. However, the performance of these models is basically dependent on an adequate understanding of the hydrological behavior in the area under study and the availability of data regarding the properties of the groundwater system. Unfortunately, data on these two conditions are often unavailable in Taiwan, resulting in the simulation results always being subject to uncertainty. Analytical models are generally considered fast tools for quantifying the drawdown response to the extraction of groundwater from wells. The best-known analytical models are the transient-state solution presented by Thies (Theis 1935) and the steady-state solution developed by Thiem (Theim 1906). For convenience, the steady-state Thiem solution is written as follows (Fetter 2014):

$$s = \frac{Q}{2\pi T} \ln\left(\frac{r}{R}\right), \quad (4)$$

where s is the drawdown caused by extraction [L]; Q is the extraction rate [L³/T]; T is the aquifer transmissivity [L²/T]; r is the radial distance from the center of a single extraction well [L]; and R is the radius of influence. It is implied that the drawdown is proportional to the ratio of actual groundwater utilization to aquifer transmissivity.

Thus, $\frac{Q}{T}$ is used to represent the drawdown index used to evaluate the impact caused by pumping on aquifer. .

3 Results and Discussion

3.1 Determining Safe Groundwater Quality Zones

To determine the regions where the groundwater quality is safe for various purposes, we first map the spatial pattern of each individual hydrochemical parameter using the OK method. Prior to computing the semi-variograms based on Eq. (1), a histogram analysis is done for each individual hydrochemical parameter. Basically, the results of the histogram analyses show the measured concentration for each individual hydrochemical parameter which more satisfactorily fit a lognormal distribution rather than a normal distribution. Accordingly, we use the log transformations of the observed hydrochemical parameters for computation of the semi-variograms. The computed experimental semi-variograms are then analyzed to obtain the best fits against the values of three important parameters, namely the nugget effect, sill and range for the theoretical semi-variogram models as defined in Eqs. (2a)-(2c). After the best theoretical semi-variogram model for each individual hydrochemical parameter is obtained, the natural logarithm of each individual hydrochemical parameter for each cell is computed based on Eq. (3) and the exponential recovery of the computed logarithm value of each hydrochemical parameter for each cell is then carried out to obtain the real spatial distribution of each individual hydrochemical parameter. For spatial mapping of the hydrochemical parameters, the study area is spatially discretized into a grid system of 40 × 40 cells with 100 m spacing in both the south-north and west-east directions. Only 447 active cells fall into this study domain. To give a more accurate estimate of model prediction performance, cross-validation tests for the kriging approaches of all groundwater quality items are performed. In cross-validation test, a sample of monitored data is removed individually and

estimated from the remaining monitored concentrations. The mean standard error (MSE) and mean square standard error (MSSE) are used to evaluate the model prediction performance. The MSE and MSSE are mathematically written as

$$MSE = \frac{1}{N} \sum_{i=1}^N \frac{Z^*(x_i) - Z(x_i)}{\sigma_k(x_i)} \quad (5)$$

$$MSSE = \frac{1}{N} \sum_{i=1}^N \frac{(Z^*(x_i) - Z(x_i))^2}{\sigma_k^2(x_i)} \quad (6)$$

where $Z^*(x_i)$ and $Z(x_i)$ are the estimated and measured values at the i th observation locations, respectively; N is the number of total measured data; $\sigma_k(x_i)$ and $\sigma_k^2(x_i)$ are kriging standard deviation and variance, at the i th observation locations, respectively. The calculated values of MSE and MSSE are close to nil and unity, demonstrating that the model prediction performances are excellent. Moreover, an accepted tolerance error with $+3(2/N)0.5$ for MSSE recommended by Chilès and Delfiner (1999) is also used as a criterion for the performance test. The values of MSE MSSE for all groundwater quality items fall within this accepted criteria. Figure 3 maps the spatial distributions of some important hydrochemical parameters. The groundwater quality values monitored for the wells are also included in the figure for comparison. It can be seen that the geographical distribution of zones with different concentration categories contains the same concentration categories as for the sampled wells. The excellent agreement between the concentrations obtained from the kriging approach and the actual monitored concentrations demonstrate the excellent model prediction performance of the kriging approach. Next, the safe regions for drinking, irrigation and aquaculture are screened by comparing the computed values for the hydrochemical parameters in each cell against the water quality standards for drinking, irrigation, and aquaculture. A cell is defined as safe for a specified utilization purpose if all estimated hydrochemical parameters values in this cell are less than the threshold values specified for the various water quality standards. Figure 4 depicts the regions where groundwater quality is safe for drinking, irrigation, and aquaculture. The peripheral northern, western and southern areas of the Lanyang Plain including the townships of Toucheng, Jiaoxi, Yuanshan, Nanao and Tatong are classified as regions where groundwater is safe for drinking. It should be noted that the cells that are classified as having groundwater quality that is unsafe for drinking include the major townships of Lodong and Ilan which are heavily populated. Almost all of the cells, except in the eastern coastal areas, groundwater quality is classified as safe for irrigation. The cells that groundwater quality are classified as safe for aquaculture cover a large portion of the western mountainous areas and upper and lower portions of the eastern coastal areas. The area percentage of cells that groundwater quality is classified as safe for drinking, irrigation and aquaculture are 37.4, 92.2 and 62.9%, respectively. In short, groundwater quality in the eastern coastal regions is less safe for drinking, irrigation and aquaculture.

3.2 Determining the Low Drawdown Regions

Mitigation of the potential negative impact on the aquifer such as a reduction in groundwater levels caused by groundwater resource development is crucial for a sound management plan for groundwater utilization. In this study, a representative drawdown index, $\frac{Q}{T}$, which is defined

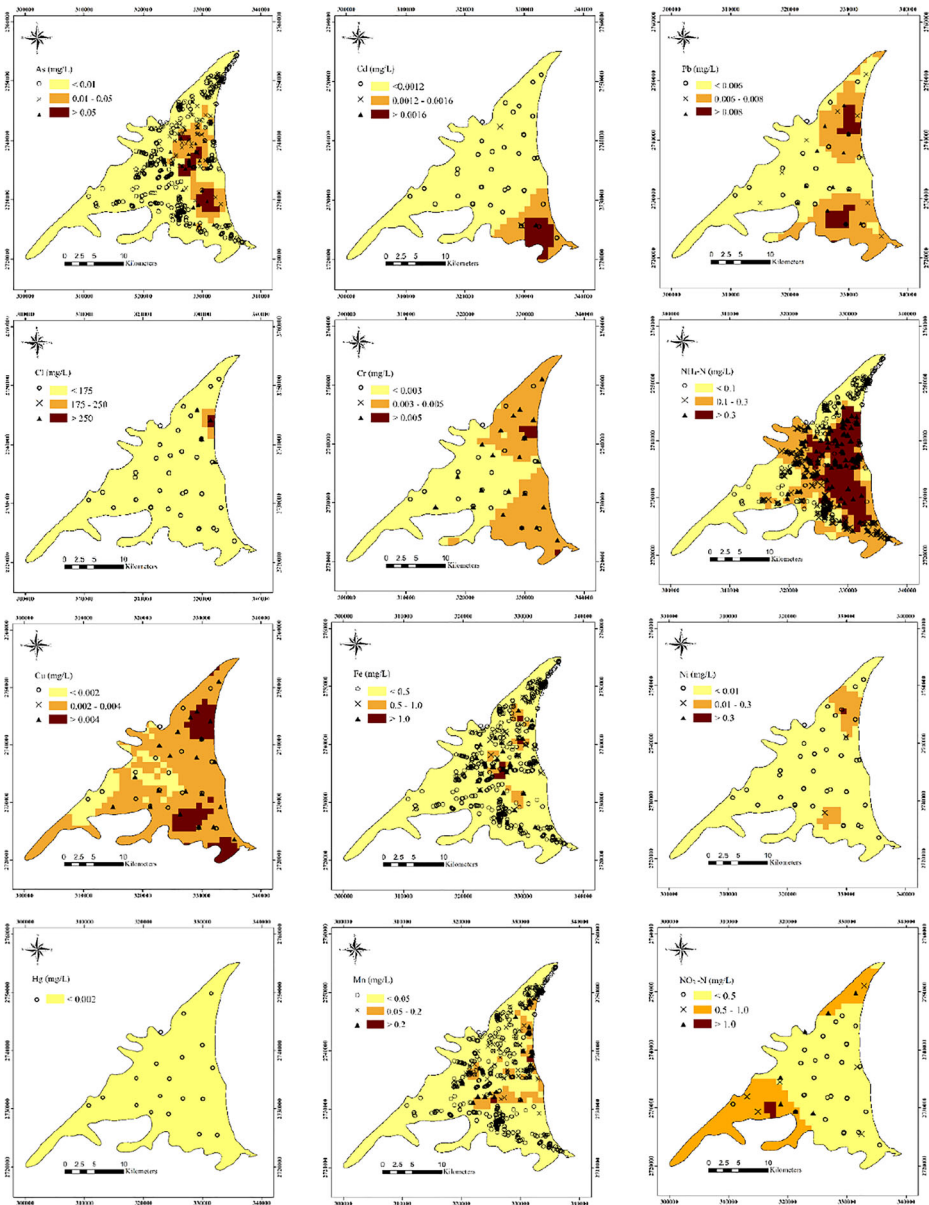


Fig. 3 Geographical distribution of some important hydrochemical parameters for the Lanyang Plain

as the ratio of the actual groundwater utilization rate (Q) to the aquifer transmissivity (T) is used. Data for aquifer transmissivity is obtained from the Taiwan Central Geological Survey (2013). Determination of the spatial distribution of aquifer transmissivity and procedure for the cross-validation test are similar to the process for determining the spatial distribution of hydrochemical parameters. The actual groundwater utilization rate in the Lanyang Plain is difficult to estimate. Here, the groundwater utilization rate is evaluated based on data for groundwater rights issued by the government. Water resource users, such as irrigation

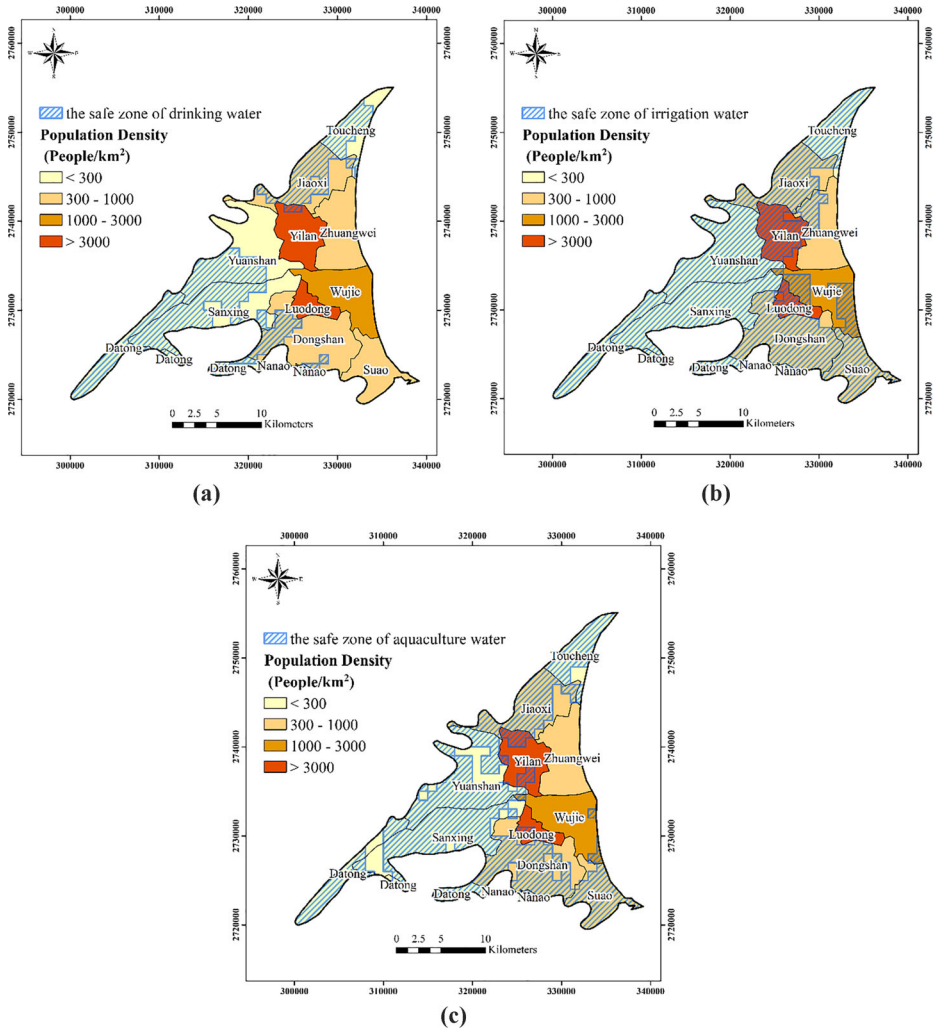


Fig. 4 Delineation of regions where groundwater quality is safe for different demands in the Lanyang Plain: (a) drinking; (b) irrigation; and (c) aquaculture

associations, the Taiwan Water Corporation, and other agricultural and aquaculture corporations must apply for groundwater rights according to the current legal rules. Data for groundwater right applications are published for individual township. Thus, we assign the groundwater utilization rate for individual township to cells that fall within a single township. For a cell that falls into two or more townships the groundwater utilization rate at this cell is calculated based on a linear combination of the product of the area percentage for the individual townships within the cell and the groundwater utilization rate for the individual township. A threshold value is specified in order to distinguish between a low and high drawdown index ($\frac{Q}{T}$). However, the selection of this threshold value is inevitably subjective although it does significantly affect the delineation of low drawdown index regions. In this study, the specified threshold value is $\frac{Q}{T} \leq 4$. Fig. 5 shows the geographical distribution of the low drawdown index regions determined based on the specified threshold value ($\frac{Q}{T} \leq 4$) regions

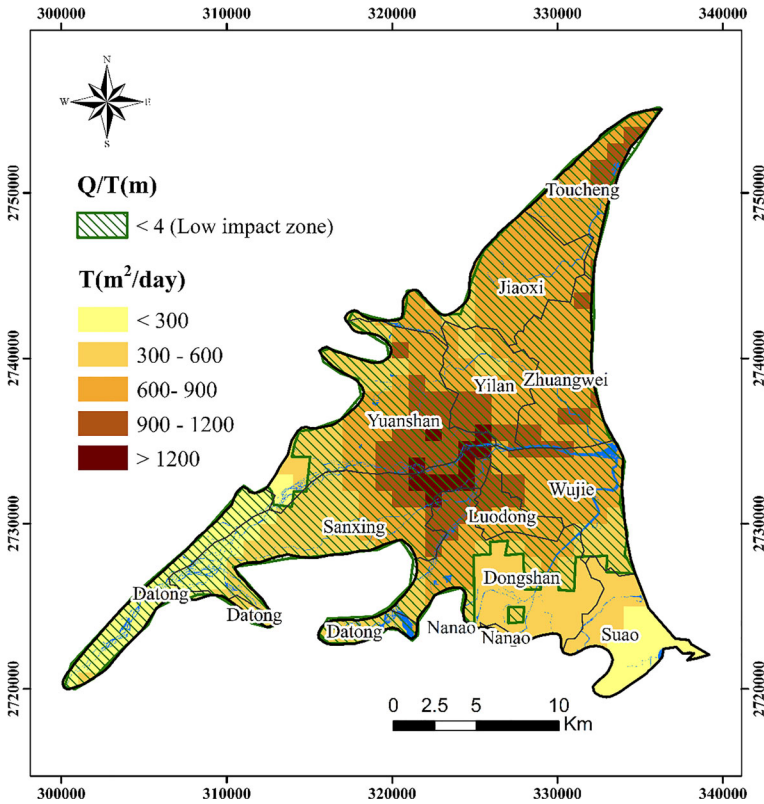


Fig. 5 Geographical distribution of low drawdown index regions based on the specified threshold value of $\frac{Q}{T} = 4m$

highlighted in green. It can be found that southeastern coastal areas of the Lanyang Plain cannot be considered low drawdown index regions.

3.3 Sound Management Plan for Multi-Purpose Groundwater Utilization

A sound management plan for multi-purpose groundwater utilization is delineated by integrating the mapping results of the regions where groundwater is safe and the regions where the drawdown index is low. Figure 6 presents a map for multi-purpose groundwater utilization based on safe groundwater quality and a low drawdown index. The cells are categorized as single-purpose, dual-purpose or triple-purpose. The area percentage of each category is tabulated in Table 3. The area percentage is defined as the ratio of the area for each category compared to the total area of the Lanyang Plain. The map for multi-purpose groundwater utilization is then compared with the current land use information to evaluate the appropriateness of current land use practices. The land use information is obtained from the Land Use Investigation of Taiwan by the National Land Survey and Mapping Center of Ministry of Interior, Taiwan. Figure 7 shows the comparison between the current usage of land for farmlands and fishponds with the multi-purpose groundwater utilization plan developed in this study. The regions where groundwater quality is unsafe for irrigation or aquaculture or the drawdown index is high are highlighted in red. Overall, 47% of the land area of the Lanyang

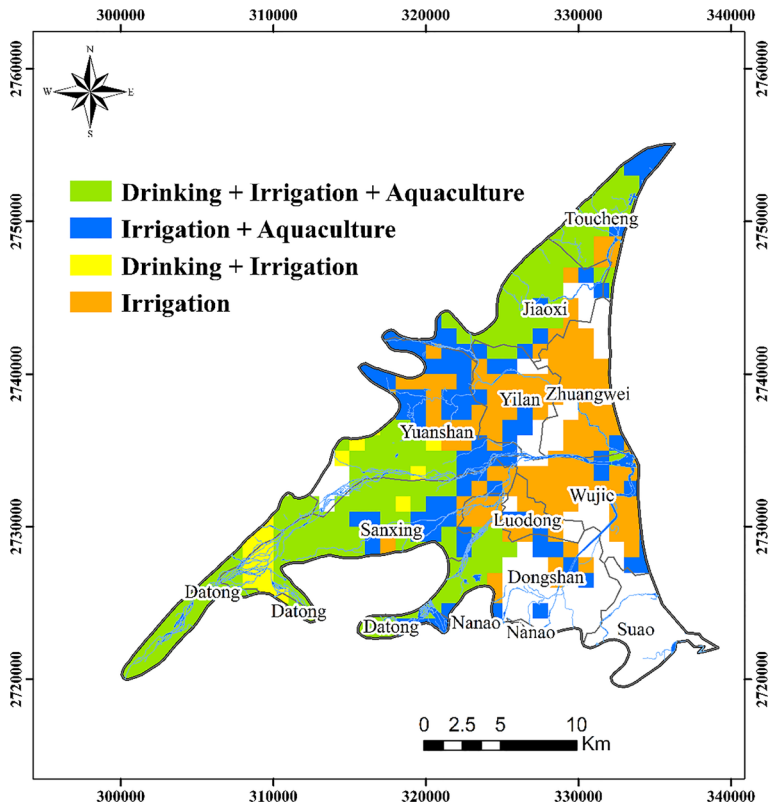


Fig. 6 Zonal management plan based on the safe groundwater quality zones for different groundwater utilization purposes and a low drawdown index

Plain is used for agriculture. The area percentage of all agricultural land in the Lanyang Plain where groundwater quality is unsafe or the drawdown index is high is 20.01%. We find that the regions unsuitable for agriculture are mostly located in the eastern coastal areas including the townships of Yilan, Luodong, Jiaoxi, Zhuangwei, Wujie, Dongshan Suao. Only 10% of the total land area of the Lanyang Plain is used for aquaculture but as much as 69.29% of these regions are actually unsuitable for this purpose.

A sound management plan for the multi-purpose utilization of groundwater in the Lanyang Plain can be developed based on this study to help government administrators to develop measures to protect groundwater resource. For zones with unsafe groundwater quality, identification of the source of contamination is the first priority followed by control of the source. Control could include the use of legislation or regulation to control contamination and public education to raise community awareness and change the anthropogenic activity leading to groundwater contamination. Land use planning is also an effective measure to control contamination. Besides control of the contamination source, intensive groundwater monitoring of the unsafe zones is required. Moreover, the government needs to develop safe water resources as alternatives to using unsafe groundwater. For zones with a high drawdown index the use of legislation to reduce groundwater exploitation is required. Land use practices need to be change in regions where groundwater quality is unsafe for irrigation or aquaculture but is currently being used for farmlands and fishponds.

Table 3 Area percentage of area of seven categories of groundwater use for regional management plans

Suitable water usage	Percentage (%)
D + I + A	34.92
D + I	2.81
I + A	17.28
D + A	0
D	0
I	20.98
A	0
Σ	76.01

Area percentage is defined as the ratio of the area of each water usage classification to the total area of the Lanyang Plain. It is divided into drinking water (D), irrigation water (I), aquaculture water (A), two-in-one (D + I, D + A, I + A) or three in one (D + I + A)

4 Conclusions

This study aims to facilitate the development of a sound management plan for the multi-purpose utilization of groundwater in the Lanyang Plain by geographically delineating the regions where water quality is safe for various requirements and regions where the drawdown index is low. The findings show that the regions where water quality is unsafe for drinking are located in the major administrative townships of Lodong and Ilan which are heavily populated.

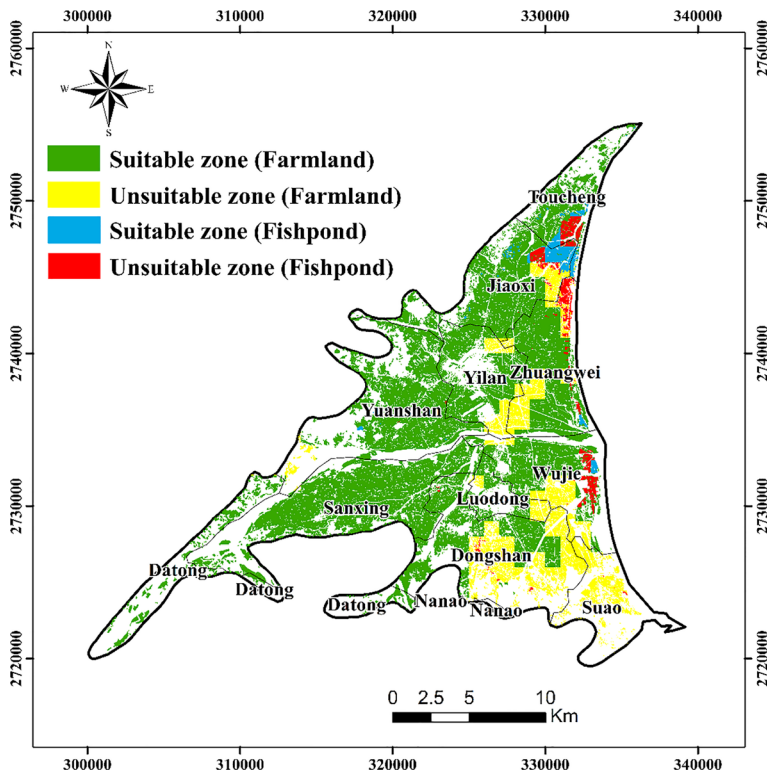


Fig. 7 Geographical visualization of current land used for farmlands and fishponds with the regions where groundwater quality is safe for irrigation or aquaculture and the drawdown index is low

Almost all regions except for the eastern coastal areas are safe for irrigation. Computation of the drawdown index which is defined as the ratio of actual groundwater utilization rate to the aquifer transmissivity shows that high drawdown index regions are located primarily in the southeastern coastal areas of the Lanyang Plain. Comparisons shows that 20.01% of the current agricultural land suffers from unsafe irrigation groundwater quality or is subject to high drawdown index and 69.29% of the fishponds are in unsafe aquaculture water quality or high drawdown index regions. The results of our study can help government administrators to adopt measures to replace groundwater withdrawal with a supply of treated surface water to protect the health of individuals and alleviate high drawdown problems caused by the overexploitation of groundwater resources and to review the current land use practices in these regions.

Acknowledgements The authors are grateful to the Ministry of Science and Technology, Republic of China for their financial support of this research under contract MOST 107-2410-H-242-002.

Compliance with Ethical Standards

Conflict of Interest None.

References

- AERC (Agriculture Engineering Research Center) (2009) Survey, analysis and assessment of groundwater quality in Taiwan areas in 2009. Water Resources Agency, Ministry of Economic Affairs, Executive, Yuan, Taiwan, pp 100–102
- AERC (Agriculture Engineering Research Center) (2010) Survey, analysis and assessment of groundwater quality of Taiwan in 2010. Water Resources Agency, Ministry of Economic Affairs, Executive, Yuan, Taiwan, pp 151–158
- AERC (Agriculture Engineering Research Center) (2011) Survey, analysis and assessment of groundwater quality of Taiwan in 2011. Water Resources Agency, Ministry of Economic Affairs, Executive, Yuan, Taiwan, pp 191–203
- AERC (Agriculture Engineering Research Center) (2012) Survey, analysis and assessment of groundwater quality of Taiwan in 2012–2014 (1/3). Water Resources Agency, Ministry of Economic Affairs, Executive, Yuan, Taiwan, pp 85–101
- Chilès JP, Delfiner P (1999) Geostatistics: modeling spatial uncertainty, Wiley series in probability and statistics. John Wiley & Sons, New York
- Chica-Olmo M, Luque-Espinar JA, Rodríguez-Galiano V, Pardo-Iguzquiza E, Chica-Rivas L (2014) Categorical indicator kriging for assessing the risk of groundwater nitrate pollution: the case of Vega de Granada aquifer (SE Spain). *Sci Total Environ* 470-471:229–239
- Fetter CW (2014) Applied hydrogeology, Fourth edn. Pearson, Harlow
- Harbaugh AW, McDonald MG (1996) Programmer documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite difference groundwater flow model. USGS Open-File Report: 96-486
- Jang CS, Chen SK, Kuo YM (2012) Establishing an irrigation management plan of sustainable groundwater based on spatial variability of water quality and quantity. *J Hydrol* 414-415:201–210
- Jang CS, Lin CW, Liang CP, Chen JS (2016a) Developing a reliable model for aquifer vulnerability. *Stoch Environ Res Risk Assess* 30(1):175–187
- Jang CS, Chen CF, Liang CP, Chen JS (2016b) Combining groundwater quality analysis and a numerical flow simulation for spatially establishing utilization strategies for groundwater and surface water in the Pingtung plain. *J Hydrol* 533:541–556
- Jean JS, Bundschuh J, Chen CJ, Guo HR, Liu CW, Lin TF, Chen YH (2010) The Taiwan crisis: a showcase of the global arsenic problem. CRC Press, New York 201pp
- Journel AG, Huijbregts CJ (1978) Mining geostatistics. Academic Press, San Diego, CA, USA

- Lee JJ, Liu CW, Jang CS, Liang CP (2008) Zonal management of multi-purpose use of water from arsenic-affected aquifers by using a multi-variable indicator kriging approach. *J Hydrol* 359:260–273
- Liang CP, Jang CS, Chen JS, Wang SW, Lee JJ, Liu CW (2013) Probabilistic risk assessment for inorganic arsenic daily intake through seafood consumption of local residents in arsenic affected areas in Taiwan. *Environ. Geochem Health* 35:455–464
- Liang CP, Wang SW, Kao YH, Chen JS (2016b) Health risk assessment of groundwater arsenic pollution in southern Taiwan. *Environ Geochem Health* 38(6):1271–1281
- Liang CP, Jang CS, Chen JS (2016a) Zonal management of multi-purposes groundwater utilization based on water quality and impact on the aquifer. *Environ Monit Assess* 188(7):431. <https://doi.org/10.1007/s10661-016-5414-0>
- Liang CP, Chien YC, Chen CF, Chen JS (2017) Spatial analysis of human health risk due to arsenic exposure through drinking groundwater in Taiwan's Pingtung plain. *Int J Environ Res Public Health* 14:81. <https://doi.org/10.3390/ijerph14010081>
- Lin CW, Kao MC (1997) Geologic map of Taiwan (scale 1:50,000, sheet 16): Suao. Central Geological Survey of Taiwan, Taipei, Taiwan
- Theis CV (1935) The lowering of the piezometer surface and the rate and discharge of a well using groundwater storage. *Trans Am Geophys Union* 16:519–524
- Theim G (1906) *Hydrologische Leipzig*: Gebhardt: 56
- Varouchakis EA, Hristopulos DT, Karatzas GP (2012) Improving kriging of ground-water level data using nonlinear normalizing transformations—a field application. *Hydro Sci J* 57(7):1404–1419. <https://doi.org/10.1080/02626667.2012.717174>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Affiliations

Ching-Ping Liang¹ · Wen-Shuo Hsu² · Yi-Chi Chien³ · Sheng-Wei Wang⁴ · Jui-Sheng Chen²

¹ Department of Nursing, Fooyin University, Kaohsiung City 831, Taiwan

² Graduate Institute of Applied Geology, National Central University, Taoyuan City 320, Taiwan

³ Department of Environmental Engineering and Science, Fooyin University, Kaohsiung City 831, Taiwan

⁴ Sinotech Environmental Technology, Ltd, Taipei City 105, Taiwan